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From Design to Realization: A Validated Pipeline for Magnetic Soft Robot Fabrication and Actuation

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Abstract—**Magneto-responsive soft materials have attracted considerable attention in biomedical engineering, with applications spanning soft robotics to regenerative medicine and drug delivery. These materials are the backbone of magnetic soft robots (MSRs), enabling them to be customized with uniquely configured magnetic domains that dictate their morphological capabilities and behavior. However, reliance on intuition to configure the magnetization profile of MSRs often results in a trial-and-error design approach that consumes time and resources. To address these challenges, this study optimizes an existing intelligent framework that uses a Covariant Matrix Adaptation Evolutionary Strategy (CMA-ES) in conjunction with a Material Point Method (MPM) simulation environment to determine the magnetization profile of voxel-based MSRs to achieve ultimate performance. This study shows that unique, non-intuitive designs can be evolved. Importantly, this intelligent design framework is linked to physical prototyping through additive manufacturing to realize these designs. Experimental validation of the generated designs confirms that the algorithm-based MSRs achieve a 10-fold increase in walking performance compared to the intuitively designed MSRs. This study also demonstrates the ability to improve upon both specific and random magnetization profiles and the ability to adapt to design constraints such as various modes of actuation. In general, the evolutionary algorithm, combined with physical prototyping, establishes an effective and efficient framework for the optimization of MSR behavior.**

I. INTRODUCTION

The capacity of untethered small-scale robots for remote manipulation and precise navigation of confined spaces makes them promising for healthcare applications, including minimally invasive surgery, remote sensing, and targeted therapy in regions such as the brain, eyes, and blood capillaries [1], [2]. Magnetically actuated robots are particularity advantageous due to their ability to operate without on-board power, allowing them to be miniaturized. Magnetic fields can penetrate thick biological tissue while providing accurate control by varying magnitude, frequency, direction, and spatial gradients [2]. This has spurred the design of magneto-responsive small-scale robots made from flexible materials, known as magnetic soft robots (MSRs).

Determining the magnetization profile of MSRs is a critical stage in the design process that dictates the robot's behavior and morphological capability. However, there is a complex interplay between MSR attributes such as their geometry, material composition, magneto-mechanical coupling and actuating fields [3]. This multi-faceted system makes reliance on traditional trial-and-error and retrospective techniques insufficient to effectively design magnetization profiles that enable behavior beyond simple deformations.

To address the limitation of intuitive design processes, research has shifted towards systematic, robust methodologies such as physics-based modeling, deep learning, and evolutionary algorithms (EAs). MSR behavior can be numerically and analytically modeled using fundamental theories and principles of magnetism and continuum mechanics. For example, Davey et al. proposed a Material Point Method (MPM) simulation for modeling MSRs that can handle self-interactions and large deformations of MSRs under various magnetic fields [4]. Integrating these types of models with computer-based optimization techniques, such as neural networks and data-driven algorithms, facilitates the refinement of model parameters and development of bespoke magnetization profiles [5]. The drawback is that deep learning methods are computationally expensive and are limited by the data set from which they are trained.

Alternatively, EAs evolve from a relatively small set of random designs and have an unlimited search space. Specifically, Covariant Matrix Adaptation Evolutionary Strategy (CMA-ES) excels in the optimization of high-dimensional problems with non-separable underlying functions and multiple global minima [6]. In the context of MSRs, the CMA-ES is well suited to locate optimal solutions while considering the interactions of multiple variables such as magnetization strength, geometry, material composition, etc.

While leveraging automated fabrication, the objective of this study is to complete the MSR development pipeline by establishing an intelligent framework for the optimization of magnetization profiles. This study contributes: 1. optimization of an evolutionary algorithm and simulation environment to improve the design of MSRs; 2. successful prototyping of evolved designs using additive manufacturing; 3. validation of evolved designs in simulation and experiment.

II. WORKFLOW

The small-scale robot fabricated by Hu et al. is used as the comparator for this study, henceforth referred to as the original robot [7]. To realize the robot on the micron-scale, and to take advantage of the 300 μm resolution of the custom 3D printer for MSRs, the original robot is scaled down by

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60%. Following the same 9-voxel structure of the original robot and by modifying an existing CMA-ES algorithm [8], bespoke magnetization profiles are evolved to optimize the robot for ultimate travel distance. The algorithm's robustness is investigated by performing the optimization from a random set of initial individuals, from an initial intuitive design, and under the constraint of varying actuating magnetic flux densities. The robots are then configured with resulting magnetization profiles, and their walking behaviors are observed in a MPM simulation tool.

A custom MSR 3D printer with 300 μm resolution is used to fabricate the robots, and proper magnetization is verified with a cmos-magview. The robots are fabricated using hard magnetic particles embedded in a flexible UV resin. The robots are modeled in COMSOL Multiphysics 6.3. Then, voxel-by-voxel, the magnetic particles in each segment of the MSR are reoriented according to the programmed magnetization profile, and the mixture is cured. Next, to actuate the MSRs, a periodic field is generated using an electromagnetic coil system. This system consists of 3 pairs of coils for each respective axis set up to approximate a Helmholtz coil. During actuation, the motion of the MSR is captured using top- and side-view cameras. The captured footage is used to calculate the speed, which is done by tracking the center of the MSR over a short period of time (10-15 s) consisting of multiple cycles.

III. RESULTS

The CMA-ES algorithm is successful at optimizing the performance of the small-scale robot. Starting from a random population, the algorithm is capable of producing 2D magnetization profiles that allow the robots to travel faster than the original robot.

Within 100 generations, the CMA-ES at 8, 10, 12, 14, 16 mT results in maximum travel distances of 3.18, 2.12, 2.89, 3.36, 3.45 mm respectively. These results demonstrate the ability of the algorithm to adapt its search space to converge to an optimized solution. Additionally, under varying modes of actuation, the algorithm adapts the magnetization profiles such that the MSRs attain increased travel speeds, whereas the original robot exhibits relatively constant performance. The corresponding magnetization profiles generated by the algorithm are non-intuitive when compared to the original design. In simulation, the robots evolved to have a pronounced forward curvature, enabling full-body advancement with each step. This highlights the ability of the algorithm to navigate complex design spaces to explore diverse solutions.

The algorithm can also improve upon existing, intuitive designs in addition to randomly generated designs. When the algorithm is initiated with the original design, it immediately discovers a robot that outperforms the original design and continues to evolve, producing a robot that exceeds original performance by 32.8%. Similar to the original design's inchworm-like crawling behavior, the robot evolved from this design, curls into a 'C'-shape faster than the original robot. It also leaps as it takes a second step. Together, these adaptations contribute to an improved travel distance.

The optimized profiles are successfully fabricated and actuated. The printed robots can be accurately configured with desired magnetization profiles, both intuitive and bespoke profiles. Experimentally, the relative performance of the optimized robots to the original robot follows a similar trend to that observed in simulation, where faster speeds are attained at higher magnetic flux densities. Under a rotating field of 36 mT, the evolved robot bends towards the direction of travel and jumps forward on its head. This adapted behavior allows the robot to achieve a walking speed that is approximately 10-fold the original robot speed.

IV. CONCLUSION

The CMA-ES algorithm presented in this study realizes an intelligent design approach in which non-intuitive, feasible MSR profiles can be crafted without requiring human expertise or large experimental data sets. The MPM simulation serves as a valuable evaluation tool when paired with the EA. By exploring 2D design spaces, as well as multiple modes of actuation, this study demonstrates the adaptability of the CMA-ES to various design constraints. The theoretical performance of the robots designed by the algorithm is translated to real physical performance, as the 3D printed robots performed similarly to the simulated robots. This study adds to the current research landscape of MSRs by establishing a framework to design, fabricate, and actuate MSRs with 2D magnetization profiles.

Future development includes the optimization of robot size, number of segments and material properties, with the potential for multi-material configurations. Modifications to optimize for 3D magnetization directions are underway to take advantage of the full capacity of the 3D printer. In general, the proposed optimization and experimental framework is a step toward realizing the clinical applicability of MSRs. Discovering the optimal walking speed of a micrometer-scale MSR, as done in this study, could translate to faster targeted drug delivery or clinical diagnostic procedures.

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